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TENSILE FRACTURE STRENGTH OF ST CUT QUARTZ

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Abstract

The tensile fracture strengths of a total of 83 ST cut, single crystal, quartz discs were measured under a variety of experimental conditions. The major emphasis of this study was to compare the fracture strength of four different types of quartz including natural, and three synthetic grades (optical, premium Q and electronic). Since fracture strength often depends on surface finish, two different polishing techniques were also assessed. One technique used a Syton polish starting from a rough ground surface while the second technique involved a fine mechanical polish followed by a short Syton polish. A biaxial flexure test was used for measuring the tensile fracture strength on the discs which were 1 inch in diameter and nominally 0.1 inch thick.

The average fracture strength of polished samples was 21,400 psi with a standard deviation of ± 6,000 psi. There was very little difference in fracture strength for the four types of quartz and the two different polishing techniques. The differences between the average fracture strength for each category fell well within the standard deviation. Five unpolished discs were also tested and the average fracture strength was found to be 8,900 ± 800 psi. Clearly, polishing the surface serves to increase the fracture strength by better than a factor of two.

Two particular techniques for altering the surface quality were also investigated. It has been reported that chemical etching of very thin quartz discs can significantly increase the fracture strength. To test the effect of chemical etching on thick discs, ten chemically etched samples were also broken. The average fracture strength was significantly lower than for polished discs, but many of the etched samples showed numerous etch pits or channels. Some the samples had few or no etch pits or channels and these showed a fracture strength comparable to the polished samples. Another seven samples had 1600 shallow grooves (~ 1000 Å deep) ion milled into a polished surface. These samples showed no significant change in average fracture strength. In addition to the parameters mentioned above, other factors such as relative humidity, Q (from infrared measurements), and sample thickness also were found to have no correlation with fracture strength.

Introduction

This paper discusses research made on the basic tensile fracture strength of quartz. It has been over 10 years since a value for the fracture strength of quartz (~ 14,000 psi) was published[1] and this number should be re-evaluated in light of the progress made in the technology of growing and polishing quartz. The major emphasis in this study was to compare the fracture strength of discs made out of four different types of quartz. These were natural quartz and three synthetic grades (optical, premium Q, and electronic). Since fracture strength often depends on surface finish, two different sample polishing techniques were used. The electro-mechanical Q of many of the quartz discs was also measured using infrared absorption techniques. The test method used for fracturing was the biaxial flexure test. Results from these fracture tests will be presented as well as results which show the effects, on the fracture strength of quartz, of chemical etching and ion beam etched grooves about 1000 Å deep.

Sample Preparation

Eighty-three ST cut, Z-zone, 1-inch diameter and 0.1 inch-thick (after polishing) quartz discs were purchased. Both natural and synthetically grown quartz were supplied, including the three synthetic grades of optical, premium Q, and electronic. The fracture strength of a material depends upon the quality of the surface finish, where surface flaws such as scratches can concentrate the applied stress and thereby lead to fracture. Complete removal of flaws from the surface permits the strength to approach the theoretical maximum for the particular material. For comparison purposes, two different sample preparation and polishing techniques were followed.

The first polishing technique (referred to as Polish A) was simple, going directly from a 220-diamond saw blade cut finish to Syton polishing for a half hour on each surface. Syton is a chemical-mechanical polish consisting of a colloidal suspension of SiO_2 in NaOH. The second polishing technique (referred to as Polish B) was more complex. Starting with a similar 220-diamond saw finish, each surface was ground down using successively finer grit sizes of 35, 12, 9, 5, and 3 microns of alumina oxide. Next a two-step polishing sequence was employed, first using cerium oxide and then finishing with Syton. The duration of the cerium oxide and Syton polishes varied, depending upon the grade of quartz, from 2 to 5 hours for cerium oxide and 1/2 to 2 hours for Syton. Both Polish A and Polish B samples had slightly bevelled edges. For both types of samples, the mechanical wheels used were randomly varied among the different types of quartz in order to avoid any systematic errors resulting from usage of a particular wheel on a particular type of quartz.

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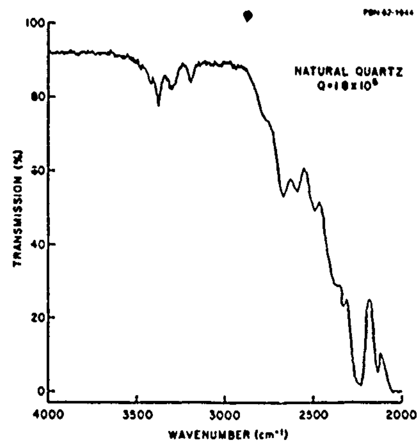
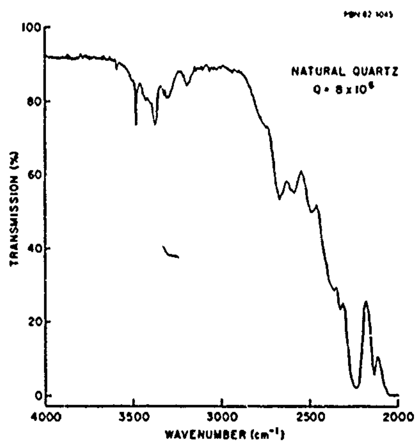
Infrared Absorption Characterization

The literature shows that there is an inverse correlation between dislocation density and electromechanical Q of quartz. High Q crystals tend to have fewer impurities than low Q crystals. There is also a direct correlation between Q and infrared absorption. Hence, infrared measurements were a convenient method for determining the Q and, therefore, the material quality of the quartz discs. All of the synthetic quartz ordered originated from Sawyer Inc., with a quoted minimum Q of 1.3 x 10^6, 1.8 x 10^6, 2.2 x 10^6 for optical, electronic, and Premium Q grade, respectively.

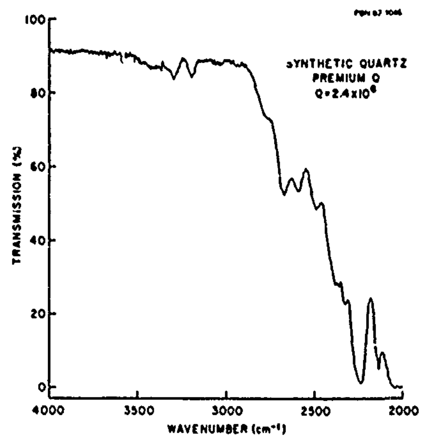
A Perkin-Elmer 580 B Infrared Spectrophotometer was used with a selected resolution of 1.4 cm^{-1} and the plotted wavenumber spectrum from 4000 to 2000 cm^{-1}. Examples of plotted infrared spectrum measurements of natural and synthetic quartz are shown in Fig. 1. With natural quartz, great differences were seen in the level of absorption at a given band. This indicates that the impurity content is distinctly variable from sample to sample. This is not surprising considering the different origins, growth conditions, and environmental factors forming each natural quartz stone out of which one to two quartz discs were cut. Because of the large variations, infrared spectrum measurements were made on each natural quartz disc. For synthetic quartz, little variation was seen in the infrared spectrum from disc to disc within a particular grade, hence only a sampling of the disc were measured.



(a) Natural quartz



(b) Natural quartz (note that this spectrum is quite different from above)



(c) Synthetic quartz

Figure 1. Infrared transmission spectra for two samples of natural quartz and one of synthetic quartz: Note that sample-to-sample variation in natural quartz can be quite large, whereas all synthetic samples of a given quartz grade were quite similar.

The equation used for converting infrared transmission levels into Q was obtained from a paper by Philips Research Labs.[2] The basic equations used are as follows:

$$\alpha_{3500} = \frac{1}{t}\left(\log \frac{T_{3800}}{T_{3500}}\right)$$

$$\alpha^*_{3500} = \alpha_{3500} + 0.25$$

Where

α_{3500} = Extinction coefficient at wavenumber 3500 cm^{-1}

α^*_{3500} = Extinction coefficient with the correction factor shown above.

t = Thickness of sample in centimeters.

T_ν = Fraction of incident light of wavenumber ν transmitted by sample

$$Q = 1.35 \times 10^5/\alpha^*_{3500}$$

Two other calculation methods for Q were assessed where one used a 3410 cm^{-1} line[2] and the other used a different equation.[3] They all resulted in somewhat different values of Q for a sample. However, the equation above generally gave a Q between the high and low values.

For natural quartz, the Q varied from 0.3 to 4 x 10^6. Most values fell into the range from 0.7 to 1.1 x 10^6. Synthetic samples nearly always satisfied the minimum Q quoted. A major limitation on the accuracy of the infrared measurements and hence the calculated Q was the thickness of the quartz discs. The literature[2] recommends at least 7-mm thick samples to provide sufficient infrared absorption for high Q material. Although our disc were only 2.54 mm thick, the low Q of most of the natural quartz samples provided high enough absorption that accurate measurements could be made. For the higher Q material, which included a small fraction of the natural and all of the synthetic quartz, two or three discs were stacked together to provide improved accuracy.

Biaxial Flexure Test and Experimental Conditions

Though there are a number of techniques for measuring tensile fracture strength, the biaxial flexure test[4] was chosen, since this technique has been used for years at Raytheon to measure the strength of optical and ceramic materials and also a large number of samples can be easily handled with this method. In this test, a 1-inch circular sample is supported below by a somewhat larger ring and is loaded above by a ball (5/8 inch diameter) with a machined flat surface (1/2 inch diameter). For an isotropic material, this creates a large area of uniform tensile stress directly under the area loaded by the ball.[5] The bottom surface of the specimen is under tension. Once loading and specimen deformation begins, the upper loading occurs along a ring having the diameter of the flat region of the ball; hence, edge preparation is not of major importance, so that sample preparation is relatively easy. Figure 2 shows the load fixture and Fig. 3 shows the Instron universal testing instrument on which the tests were conducted.

The fracture strength of the quartz discs was determined by loading the samples until fracture occured. The load force at fracture was recorded and this was used to calculate[5] the tensile stress from the equation below.

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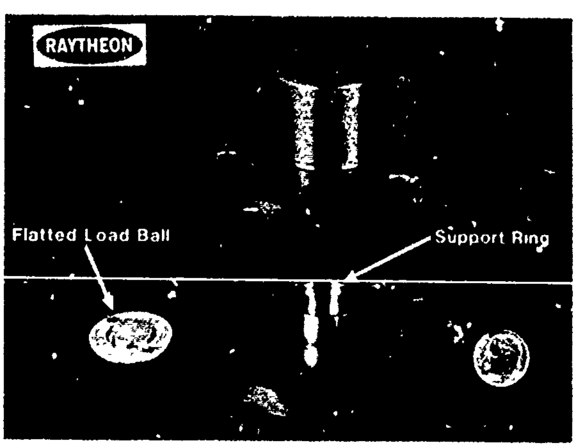

Figure 2. Load fixture for biaxial flexure test.

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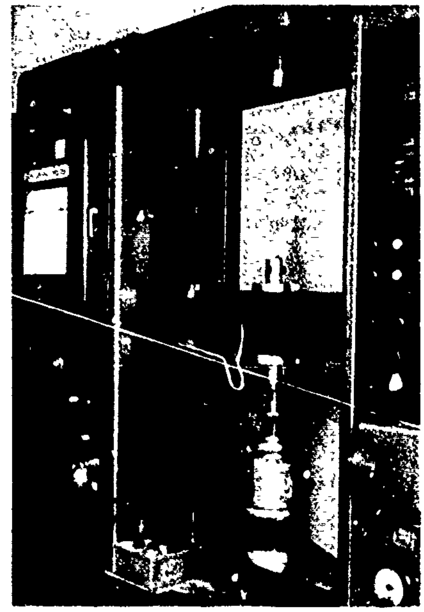

Figure 3. Instron universal testing instrument used for loading the quartz discs.

$$\sigma_r = \frac{3}{2\pi}\left[(1-\gamma)\,\frac{a^2-r_o^{\,2}}{2b^2} + (1-\gamma)\ \ln a/r_o\right]\frac{P}{t^2}$$

Where

γ = Poisson's ratio

a = Radius of supporting ring

r_o = Radius of flat on load ball

b = Radius of quartz disc

P = Load force (in pounds)

t = Sample thickness (in inches)

The values used for the various parameters are: $a = 0.420$ inch, $r_o = 0.25$ inch, $b = 0.50$ inch, and $\gamma = 0.16$. The value used for Poisson's ratio was that of fused quartz. This obviously is not the correct value for single-crystal quartz, but the anisotropy of crystalline quartz means there is no single value. The above equation for tensile stress is not strongly dependent on γ, however, so the exact choice of a value for γ is not critical. A 25 percent change in γ causes only a 4 percent change in σ_r.

It was impossible to conduct the tests in a fully controlled environment, but temperature and humidity were recorded during each test to provide for evaluation of any possible correlations between these parameters and the observed fracture strengths. The tests were conducted at room temperature which, through the course of the tests, showed only a small peak-to-peak variation of about 4°F. The relative humidity, however, ranged from 46 percent to 72 percent over the duration of the tests. A special test designed to reduce the effect of humidity on tensile strength was performed and will be discussed in the next section.

During the course of the fracture tests on the first two samples, it was necessary to stop the application of increasing load in order to make adjustments in the recording equipment. In both cases the samples fractured after several tens of seconds at a high but constant load. This phenomenon is known as delayed fracture and results from a slow crack propagation velocity. Since this introduced a time-dependent variable into the fracture strength, great care was taken to ensure that all subsequent tests were made at a fixed load rate. This rate was 1300 lb/min which gave a typical time from the start of the test to fracture in the range of 15 sec to 45 sec.

In order to prevent the introduction of another variable, all of the samples (with the exception of some with strain gauges) were placed on the support ring with their x axis pointing in the same direction. Also, since very high load forces (350 to 1000 lb) were required to fracture the discs, some damage to the support ring was incurred during each test. To prevent this from becoming a factor in the fracture strength, the support ring was dressed after every seventh test. No significant damage was incurred on the load ball throughout the tests.

A final comment on the experimental procedures: one assumption of the biaxial stress test is that once the sample bends under the load force, the only region of contact between the flatted load ball and the sample surface is at the outer edge of the flatted area. Since quartz is a very hard and brittle material, it was decided to test this assumption by replacing the flatted area with a ring of the same diameter for a few tests. Two samples were broken in this manner and their fracture strengths were completely in line with other samples fractured in the normal manner. Therefore, all remaining discs were fractured with the flatted load ball.

Fracture Results from Main Group

The main group of samples consisted of 50 discs prepared as previously discussed. Of these 50 discs, 15 were natural quartz, 14 optical grade, 14 premium Q, and 7 electronic grade. Polish B was used on 22, while the remaining 28 had Polish A. This group of 50 samples provides the main body of data from which the effect of grade of quartz and type of polish could be evaluated. It also provides a baseline to which some special cases could be compared. These special cases (involving 30 additional discs) will be discussed in the next section.

Table 1 shows the average fracture strength (in psi) and standard deviation for each of the seven combinations of the type of quartz and the polishing technique as parameters that were tested. No electronic grade samples with Polish B were used. The far right column and bottom row show the combined results from the columns to the left or the rows above, respectively. During the fracture tests, the samples were broken in groups of seven (one sample for each parameter) so that any systematic variable could be minimized. The average fracture strength for the entire popoulation was 21,400 psi, but two other characteristics are quite noticeable. One is that the standard deviation is quite large (~ 30 percent), and that any differences in fracture strength among the seven

TABLE 1

FRACTURE STRENGTH OF ST CUT QUARTZ DISCS

	Polish B	Polish A	Polish A & Polish B
Natural	(8) 21,600 ± 7,600	(7) 20,900 ± 5,200	(15) 21,400 ± 6,300
Optical	(7) 24,400 ± 6,400	(7) 23,200 ± 8,100	(14) 23,800 ± 7,100
Premium Q	(7) 19,400 ± 4,200	(7) 20,100 ± 4,400	(14) 19,700 ± 4,200
Electronic	--	(7) 20,400 ± 6,100	(7) 20,400 ± 6,100
Total	(22) 21,800 ± 6,300	(28) 21,100 ± 5,900	(50) 21,400 ± 6,000

(N) = Number of samples. All values in psi.

TOTAL POPULATION (N=50) 21,400 ± 6,000 psi

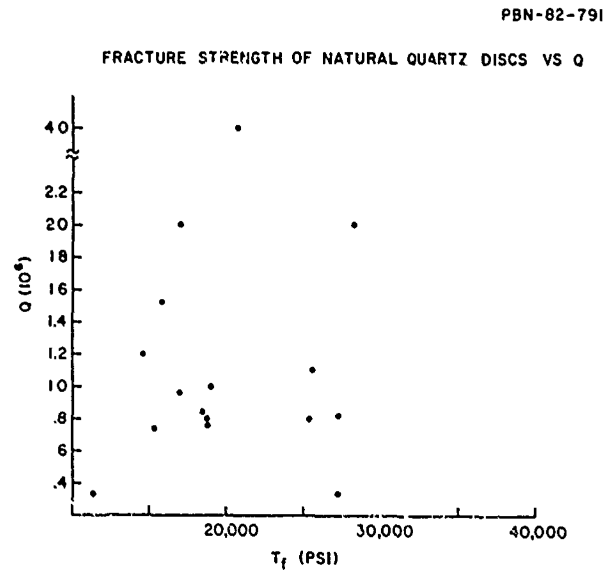

Figure 4. Fracture strength of natural quartz discs relative to their measured Q values.

parameters are small compared to the standard deviations. Virtually no difference existed between Polish A and Polish B samples. More variation among the types of quartz was observed, but even between the strongest (optical) and weakest (Premium Q) the difference was only 4,100 psi. This is only slightly more than 2/3 of the average standard deviations. Also, no correlation was observed between the measured Q of the natural quartz and the fracture strength. This is shown in Fig. 4.

In view of the large standard deviations, it is of interest to investigate the distribution of fracture strengths. Figure 5 shows the distribution for the entire population of 50 discs. As can be seen, the distribution is not symmetric but has a tail which stretches up to nearly 40,000 psi. Yet, the peak of the distribution lies somewhere between 15,000 and 20,000 psi. The ratio of the strongest to weakest sample is a very large 2.85. Figures 6 and 7 show the fracture strength distribution for the Polish B and Polish A samples separately. Both show the same general shape as the distribution for the entire population. In these figures, the grade of quartz for each data point has been indicated by a letter (N = natural, O = optical, etc.)

In addition to the fracture strength of each disc, seven of the first samples were broken with strain gauges on them. The strain gauges were located on the bottom side of the discs (the side under tensile stress). Four were oriented so as to measure the strain along the x axis, while the other three were oriented to measure the strain along the direction perpendicular to the x axis. The strain at fracture ranged from 1.2×10^{-3} to 1.6×10^{-3} for seven samples. In the x direction the average ratio of stress to strain was $17.9 \pm 1.0 \times 10^{7}$ psi.

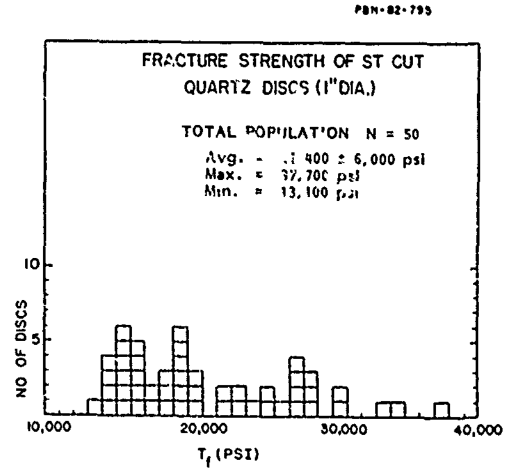

Figure 5. Distribution of fracture strengths for the main group of 50 discs.

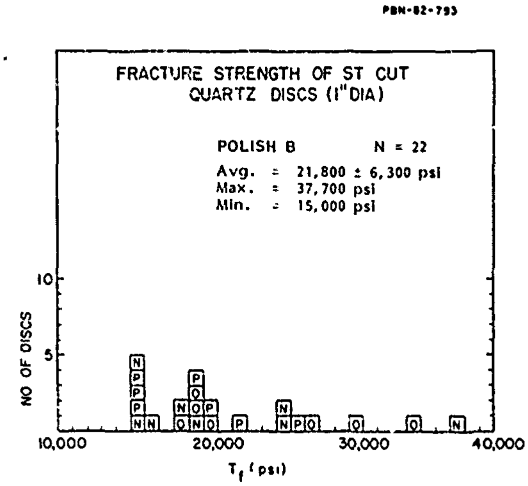

Figure 6. Distribution of fracture strengths for the Polish B discs. The grade of quartz is shown for each sample, N = natural, O = optical, P = premium Q.

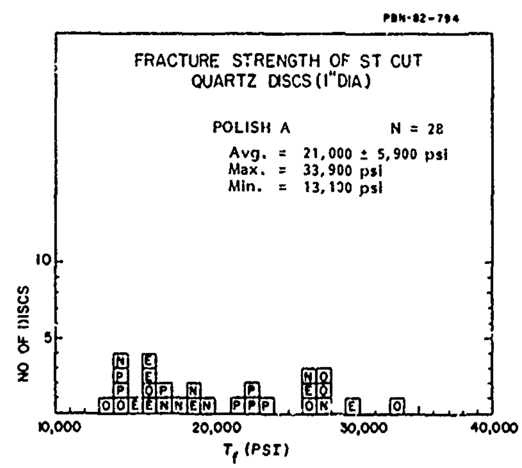

Figure 7. Distribution of fracture strengths for the Polish A discs. The grade of quartz is shown for each sample; N = natural, O = optical, P = premium Q, E = electronic.

In the direction perpendicular to the x axis, the ratio was $17.5 \pm 0.9 \times 10^7$ psi.

Some observations made during the course of the tests led to minor changes in test conditions. One observation was that the average fracture strength of the 7 discs with strain gauges was 25,000 psi while the next 14 discs, without strain gauges, averaged 21,000 psi. This led to some concern that the strain gauges effected the fracture strength. To check this, the next 7 discs were broken with a piece of thin plastic, similar to a strain gauge, fastened to the disc in the same manner as a strain gauge. The average strength of these 7 discs, however, was found to be 21,400. This seemed to rule out the strain gauges as a cause for the high strength of that particular group.

Since the relative humidity was increasing through the course of the fracture tests, it was also decided to evaluate the effect of humidity on fracture strength. Therefore, a special test was arranged for the final 14 of the 50 discs. Seven were broken as usual, but the other seven were baked at 175°C for 4 hours to drive off absorbed water. While hot, one surface was coated with a silicon grease and then the discs were stored in dry nitrogen (at room temperature) until immediately before they were to be fractured. The greased side was placed down so as to be under tension. Though the humidity was high during these tests, both groups showed above-average strengths and little difference was observed between the greased and ungreased samples. Since neither the dummy strain gauges or the silicone grease had any significant effect on fracture strength, these parameters were not called out in Table 1. In hindsight, it appears that our concerns about systematic affects were caused by statistical fluctuations related to the large standard deviation.

The statistical theory of brittle materials is commonly based on the Weibull probability distribution. The relationship between probability of failure (P_f) and applied stress is:

$$P_f = 1-\exp\left[-\left(\frac{\sigma}{\sigma_o}\right)^m\right]$$

where σ is the maximum stress at fracture and σ_o and m are material constants. The Weibull modulus is represented by m. Figure 8 shows a plot of the Weibull distribution for our samples.

The estimation of the Weibull parameter m is made by using the maximum likelihood method in ln-ln space. The weibull distribution expressed in terms of probability of survival is:

$$P_s = \exp\left[-\left(\frac{\sigma}{\sigma_o}\right)^m\right]$$

Taking the logarithm of both side yields:

$$\ln P_s = -\left(\frac{\sigma}{\sigma_o}\right)^m$$

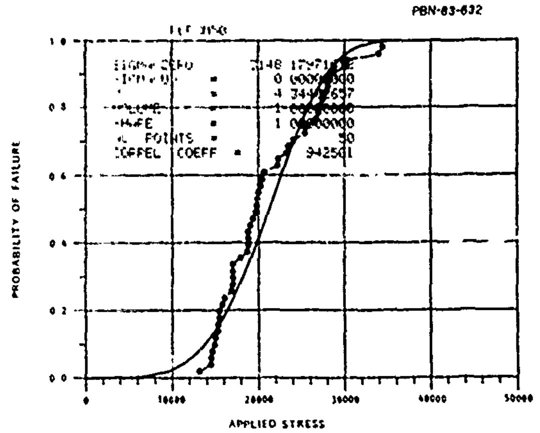

Figure 8. Weibull distribution for the total population of 50 samples tested.

Similarly:

$$\ln(-\ln P_s) = m \ln \sigma - m \ln \sigma_o.$$

Note that $\ln(-\ln P_s)$ is a linear function of $\ln \sigma$ where m is the slope and the intercept is $(-m \ln \sigma_o)$. Figure 9 shows a plot of $\ln(-\ln P_s)$ vs. $\ln \sigma$. Different Weibull modulus can indicate that more than one fracture mechanism is occuring. From Fig. 9 more than one Weibull modulus is apparent and can indicate that one type of fracture mechanism occurs for low fracture strength, and another fracture mechanism occurs for high fracture strengths. This may explain the large standard deviation that was observed.

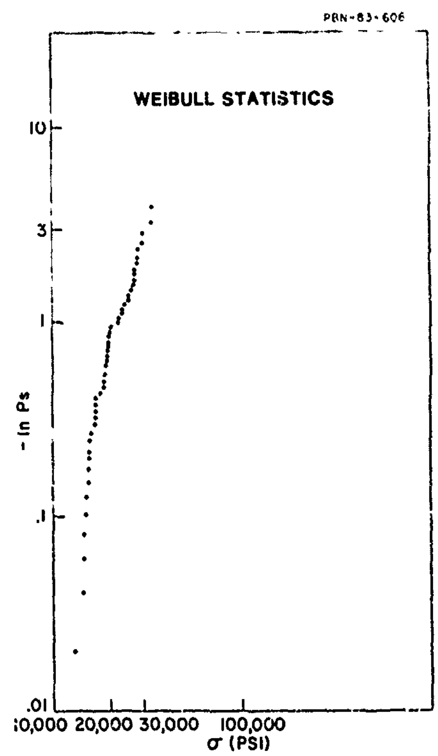

Figure 9. Ln-Ln plot of $-\ln P_s$ vs. σ where the slope is the Weibull modulus.

As a final step in evaluating the main group of discs, seven discs were reassembled in order to study the fracture patterns. When broken, the quartz shattered and the higher-strength discs disintegrated into far too many pieces to attempt reconstruction. Therefore, only the weaker discs could be reassembled. Figure 10 shows the fracture patterns of four of the seven samples along with the corresponding fracture strengths (in psi). A great deal of similarity is seen in the patterns among the four samples. All show a central section with fracture lines running completely around it and usually through it. The diameter of the central section is roughly the same as that of the flat on the load ball. In some cases, some of the fracture lines on different samples appear to be the same crystallographic planes. Outside of the central section the fracture lines tend to run radially, giving a flower petal appearance. Generally it was not possible to tell where the fracturing originated, but in one sample the central section was cracked but still intact. Obviously, for this case, the fracturing did not originate in the central section. This was unexpected since that is precisely where it is supposed to start in a biaxial stress test. This observation, in combination with the very similar fracture patterns in all seven of the reassembled samples, has led to the possibility that the fracturing of all of the samples may have started near the edge of the flat on the ball or perhaps even near the support ring. A possible explanation for this is the affect of anisotropy of a single crystal. The stress analysis for the biaxial stress test was done for isotropic materials, such as ceramics, and would not be accurate for most single crystal materials. A complete analysis for ST cut quartz discs was beyond the scope of this program, but it may show high tensile stress levels on the bottom surface, directly under the edge of the load ball. This further increases the uncertainty in the calculated values of the fracture stress. Therefore it would be best to assume that these values are a lower limit and the fracture stress may in fact be higher. The present questions about the accuracy of the calculated stress values should in no way affect the results of the comparison among different grades of quartz and types of polish.

Fracture Results from Special Groups

Thin Discs

In this special group, eight quartz discs consisting of two each of X cut, Y cut, AT cut and BT cut plates were used. The discs were 1.25 inch in diameter, 0.05 inch thick, and were polished on one side. It was determined that the discs were at least 10 years old, but the source, grade of quartz, and type of polish were unknown. The average fracture strength of the eight discs was found to be 22,110 ± 6160 psi, which is very consistent with the results from the main group. This was reassuring since these discs were considerably different in both geometery and history from the main body of samples.

The two X cut discs had the highest average strength (~ 26,700 psi) of the four different cuts, but a population of only two is insufficient to draw any conclusion about the relative strength of the various cuts.

Unpolished Discs

In order to compare the relative strengths of polished and unpolished discs, five unpolished quartz discs were broken. Of the five, four were natural quartz with a 120-μm lapped surface finish, and the average tensile strength among the four was 9200 ± 440 psi. The one remaining disc was an optical-grade quartz with a 220-diamond saw blade finish which broke at 7,600 psi. By comparison, the average tensile strength of polished discs was 21,400 ± 6000 psi. These experiments indicate, not surprisingly, that unpolished quartz is substantially weaker (by a factor of two to three) than polished quartz, and therefore that polishing is an important part of maximizing the strength of a given configuration.

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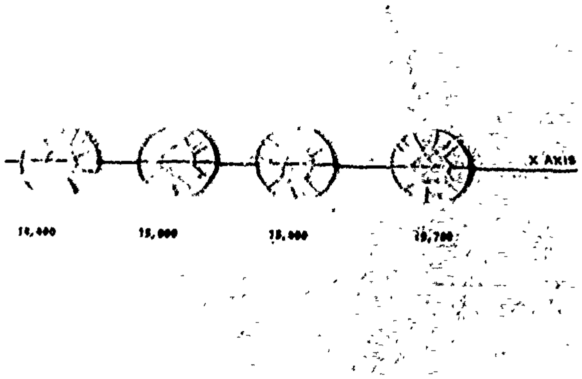

Figure 10. Fracture patterns for four quartz discs along with their measured fracture strengths. Each disc is oriented such that its x axis is parallel to the indicated line.

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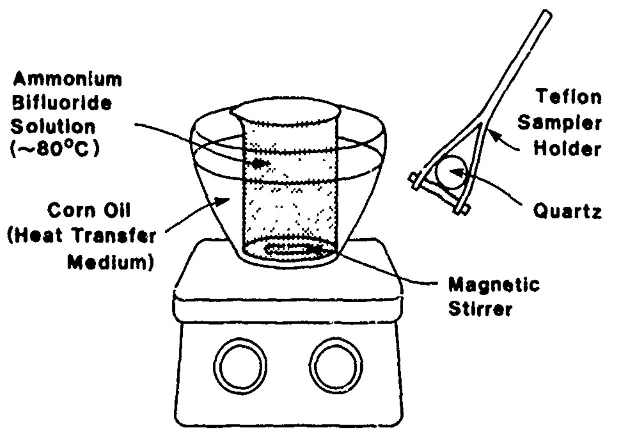

Figure 11. Experimental setup used for chemically etching quartz discs.

Chemically Polished Discs

Chemical etching of natural quartz discs in a saturated solution of ammonium bifluoride can produce chemically polished surfaces. Interest was generated because very thin chemically polished discs are shown to be extremely strong.[6] The etching experiments were performance in a double beaker arrangement, as shown in Figure 11. An outer glass beaker contains corn oil, which proved to be a better heat-conducting medium than water because of its slower evaporation rate and higher boiling point. The inner teflon beaker contains a saturated solution of ammonium bifluoride with a composition of 65 gms ammonium bifluoride flakes per 100 ml of solution. The ammonium bifluoride solution is heated to about 80°C, and is constantly agitated with a stirring bar. The rate of etching depends primarily on the temperature of the solution where the higher the temperature the faster the removal of material from the substrate. A teflon sample holder is used to hold the quartz disc in the etching solution.

Prior to etching, all discs underwent a thorough cleaning to remove surface contaminants such as grease, which may inhibit etching. The cleaning procedure consists of ultrasonic agitation in a detergent solution followed by thorough rinsing with TCE, acetone, and methanol.

Both natural and synthetic quartz discs, with either Polish A or Polish B surfaces, were chemically etched. The rate of removal from both surfaces varied from 1.5 to 2.2 mils per hour dependent upon temperature and amount of depletion of the etching solution. A total of 4 to 6 mils was typically etched off to ensure complete removal of surface layers damaged by mechanical lapping and polishing processes.

After completion of the chemical polishing, the surface topography was examined. Two commonly observed surface defects are etch pits and etch channels, as shown in Fig. 12. At the surface end of an etch channel, etch pits are always found; however, etch pits are not always associated with etch channels. The exact mechanism for generation of etch pits and channels is unclear. Etch channels are likely due to dislocations in the crystalline lattice. Bulk and/or surface defects and impurities in the quartz may lead to etch pits. One piece of evidence for a bulk-related mechanism was seen in a sample where etch pits were heavily concentrated in corresponding areas of the surface on both sides of the disc. A surface-related mechanism instead would have resulted in etch pits evenly distributed across only one surface, since the whole disc surface should have undergone the same preparation and polishing conditions.

Large numbers of etch pits and channels were observed in synthetic grade quartz. Hence, chemical polishing using ammonium bifluoride proved to be unsuitable for synthetic quartz. Though the amount of etch pits and channels varied from sample to sample, all chemically etched natural quartz surfaces were of much better quality than chemically etched synthetic quartz surfaces. Of the ten chemically etched surfaces, the average fracture strength was 14,400 ± 6500 psi, which proved to be substantially weaker than the regularly Syton polished surfaces of strength 21,400 ±

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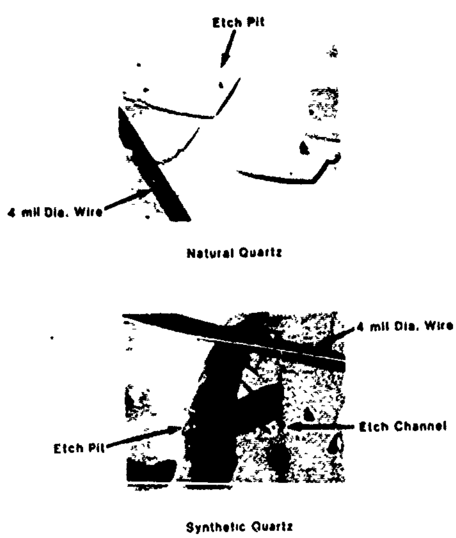

Figure 12. Photographic comparison of surfaces of natural and synthetic quartz disc after chemical etching.

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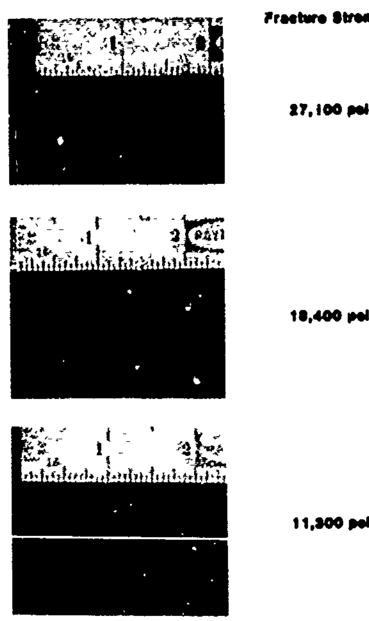

Figure 13. Three chemically polished natural quartz discs, showing the correlation between fracture strength and surface quality after etching.

6000 psi. This weakening of tensile strength due to chemical etching is contrary to results noted in the literature.[6] One important observation was that, among etched samples, the better quality surfaces with little or no etch pits had a higher fracture strength of 20,700 ± 7500 psi. Although this is not stronger than the regularly polished Syton finish surfaces, it is substantially stronger than the average strength of the general population of chemically polished samples where the surfaces were full of etch pits and channels. Hence, etch pits and channels do cause weakering of the fracture strength. Shown in Fig. 13 is this observation that the fewer the etch pits and channels on the surface, the higher the fracture strength. An interesting possibility may be first to chemically etch the surface and then finish with a slight Syton polish to smooth out the etch pits.

Discs with Ion Etched Grooves

Placing ion-milled grooves onto the surface of quartz discs and then testing for tensile strength would show the effect of the grooves on the disc structure and show whether the grooves would substantially weaken the discs.

Seven quartz discs had grooves ion-milled onto the surface using standard photolithographic techniques. The quartz is coated with photoresist. Then the photoresist is exposed through a mask with UV light. A mask with 1600 2.5 microns wide grooves was used. Following the exposure, a development step removes the exposed photoresist and hence bares the surface in the groove regions. An ion-miller is used to etch down 1000 Å into the bare substrate, and the rest of the substrate is protected by the photoresist.

The average fracture strength was 19,300 ± 2700 psi, which is comparable to regular unmilled surfaces with strengths of 21,400 ± 6000 psi. Hence, at least for discs, ion-milled grooves on the surface did not substantially weaken the tensile strength.

Conclusion

The major emphasis of this study was to compare the fracture strength of four different types of quartz including natural and three synthetic grades (optical, premium Q and electronic). A biaxial flexure test was used for measuring the tensile strength on quartz discs which were 1 inch in diameter and nominally 0.1 inch thick. The average strength of polished samples was 21,400 psi and this was independent of both quartz grade (natural quartz and three distinct synthetic grades) and polishing details. Unpolished samples, however, fractured at approximately 9,000 psi indicating that polishing is indeed a critical processing step, increasing material strength by a factor of 2 to 3. Chemical etching was also evaluated, but caused etch pits in natural quartz which actually reduced average strength. The ion-beam milling of extremely shallow grooves (1,000 Å deep) on the disc surfaces did not significantly alter material strength. In addition to the parameters mentioned above, other factors such as relative humidity, Q (from infrared measurements), and sample thickness also were found to have no correlation with fracture strength.

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